ESECUTIVE SUMMARY REPORT

MAANA-ENG-ACM-SYS-N-002 v2	Company: Maana Electric SA

SUBJECT: Accelerated Combustion of Metals for Exothermic Heating (ACME) for Lunar Night Survival

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ABSTRACT: The present document describes the first work developed by Maana Electric in the frame of the ACME project. The aim of the activity is to develop a system to use thermite reaction produced from in-situ resources from lunar regolith and use the energy released by the metallothermic reaction as a Lunar Night Survival solution. This document reports the results of the first Proof-of-Concept carried out at Maana's laboratories to validate that thermite in atmospheric condition can be generated from regolith and its beneficiated forms. From the outcomes of the PoC, a breadboard has been designed, integrated and tested. The testing with the breadboard allowed to investigate the ignition and propagation phenomena in vacuum conditions and provided several information on the behavior of different reactants combinations (LMS-1/Al, LHS-1/Al, ILM/Al and beneficiated LMS-1). Pre-processing of the regolith was also identified as potentially crucial to achieve full propagation of the reaction. Finally aspects to improve in the experimental setup have been identified to achieve a higher grade of confidence of the process.

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Executive Summary

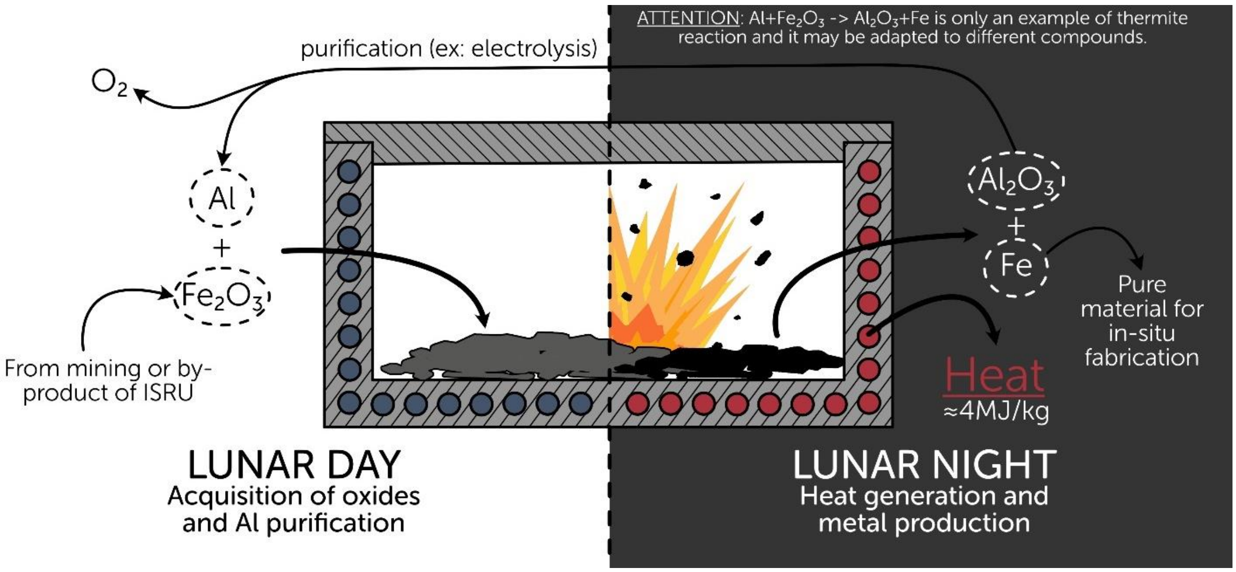
Maana Electric is a Luxembourgish deep-tech company operating in the field of photovoltaic and ISRU technologies. The company has active projects for terrestrial and space applications, with the aim to provide sustainable energy to sustain the energy market and boost human ambition on Earth and beyond. With the context of space exploration, Maana Electric focuses on system for lunar exploration, in accordance to the short and medium term objectives of the Global Exploration Roadmap. Maana Electric recognized a technological gap concerning lunar night survival systems, which are not appropriate in terms of size and sustainability for the robotic and human exploration planned for the next decades. This gap becomes evident especially for large systems which are supposed to be operative for long missions, as shown in the following table where typical requirements for lunar night survival are listed.

Mission	Thermal power [W]	Energy cycle [kWh]	Time mission [months]	Energy mission [kWh]
Lander	30	10.5	3	31.5
Rover	30	10.5	12	125
Pressurized habitat	625	219	120	25500

Employing ISRU technologies can improve the sustainability of the systems, enabling the use of local resources (for example regolith) to reduce the dry mass at launch. Maana Electric proposed, as part of the OSIP initiative, a new concept named Accelerated Combustion of Metals for Exothermic Heating (or ACME). The system, based on metallothermic (thermite) reaction, uses resources extracted and processed in-situ to provide thermal power following the general equation:

$$M1 + M2O \rightarrow M1O + M2 + Energy$$

The reaction is therefore a kind of solid-state combustion, where the oxygen is transferred between two metals (M1 and M2). The reaction occurs with the release of heat in the process proportionally (in the ideal and adiabatic case) to the difference between the formation enthalpy of the two oxides (M1O and M2O). The concept uses in-situ extracted material as oxides in their mineralogical form (M2O). Additionally, it refines metals (M2) from the reactants used from the thermite reaction which can be used in local fabrication of items (i.e. spare parts). Maana Electric conceptualized ACME as part of a closed-loop ISRU concept where the product oxides (M1O) can be recovered during lunar day and converted again in metal form (M1) with the production of oxygen. This closed-loop strategy is schematically represented in the following Figure.



The activity was deployed first through a literature review and trade-off studies to:

1) Identify the most suitable metallothermic reactions that could be generated using only chemicals that can be retrieved from the lunar regolith. Oxides with high enthalpy of formation (for example, ilmenite) has the advantage to provide more heat during the reactions, but they put additional constraints in terms of beneficiation and pre-processing of the material. As such, it was decided to focus the activity on thermite reactions with oxides with higher availability, therefore raw lunar regolith.

2) Select a method to ignite the reaction compatible with the ISRU process. Here it was proposed to use a laser to generate a high temperature ignition spot, which should be able to propagate through the rest of the reactant mass. This has the major benefit of removing any ignition component (such as an heating wire) from the high-temperature region.

3) Understand how heat generated could be stored and distributed for Lunar Night Survival. While the reaction shall occur in a space able to contain the violent heat generation (i.e. a reactor), Maana Electric identified the need to have a buffer region acting as thermal interface between the reactor and the payload. The heat can be transferred using a fluid heat exchanger integrated with such a region.

These design decisions were then tested in a Proof-of-Concept stage in laboratory conditions. The experimental campaign with the selected reactants proved that it is feasible to have thermite reaction from elements that can be mined directly on the Moon, and this provides a first validation of the concept. The experiments suggested that

Aluminum shall be preferred as metal reactant. Indeed, thermite with magnesium reaction resulted to be too violent for purposes of ACME. In addition, magnesium transportation and handling are judged hazardous and pose some risks in terms of safety. At the same time, from the oxides side, enstatite and anorthosite showed some complexity in triggering the reaction and even when the reaction is started at specific mixing ratios (which generally imply the use of more metal reactants) there is no propagation. Instead, both LHS and LMS showed similar behavior and consistent and repeatable performance. Laser ignition was also proven to be effective, even though a more accurate selection of the type of laser (tuned on the wavelength of the thermite mixture to ignite and with higher power) should have been considered. Finally, the heat produced from the reactions could be collected from the reactor and stored in a thermal accumulator.

To validate these results in more accurate environmental conditions (such as vacuum, as oxygen may have had an influence on the propagation, speed and grade of completeness of the reaction), it was suggested at the end of the PoC to design a new breadboard that could allow testing the reaction in vacuum conditions. The breadboard was composed by two main components:

1) Reaction Chamber. A cylindrical vacuum chamber that allocates the crucible containing the material. The crucible is in contact with a buffer element acting as thermal interface with a copper spiral which contains the working fluid. The system is also surrounded by a layer of insulating material. The chamber and its lid allocate the all the vacuum interfaces (electrical, data, optical, mechanical) to operate the breadboard.

2) Water tank. An insulated tank that contains the working fluid circulating to the reactor to extract the heat generated by the reaction. This component acts to simulate the heat sink (i.e. the payload) bit it also allocates the measurements equipment to quantify the performance of the system.

This breadboard could therefore allow to safe testing several combinations of thermite reactions starting from different compositions in vacuum condition, real-time monitoring of the experimental conditions, retrieving the samples from the thermite reactions for further analysis and/or processing and finally extracting, assessing and storing the energy of the thermite reactions. It also allowed to ignite the thermite with a heating wire instead of laser, to evaluate specific influence of the latter.

The functional testing of the breadboard validated the system. However, the extraction and the assessing of the energy of the reaction was not good enough as the breadboard experienced several heat losses that provided inaccurate measurements. Nevertheless, a quite extensive testing campaign was carried out using the breadboard and the following conclusions have been drawn:

- Thermite reactions from raw regolith or its beneficiated forms could be ignited in vacuum conditions. Several combinations of reactants have been tested and for each reaction the influence of the mixing ratio has been assessed.
- Except for some combinations of reactants, ignition of the thermite was always possible, while the propagation (partial or full) was not always achieved. In general, the thermite reactions from raw regolith simulants (LMS-1 and LHS-1) were more complex to perform because of low exothermic potential of the mineralogical species they are made by. Ilmenite-based mixtures have more exothermic potential and it proved to generate high energy but, if not properly triggered, it could react violently and uncontrollably. In the perspective of the implementation of the reaction into a larger ISRU architecture, solving the propagation issues of the raw regolith could be very favorable as it simplifies the overall architecture of the process. Any scenario including one or more beneficiation steps to produce ilmenite-enriched reactants has to be investigated in the next stage of the project.
- The pre-heating process proved to be crucial for the partial or full propagation of the reaction through the sample. The laser heating proved to be sufficient to ignite the reactions (especially the most energetic thermite such as the ilmenite-based one), but the localized nature of the heating process did not allow propagation through the full mixture in absence of oxygen. The Joule heating by resistive hot wires provided a bulk pre-heating of the mixture with improved propagation of the reaction. A pre-heating procedure of the sample was identified as the most promising solution to achieve full and controlled propagation.
- The products of the reactions were sensitive to the grade of propagation and the speed. Slow and controlled reactions provided more powdery and brittle structures, while fast and uncontrolled reactions were characterized by hard sintered/fused metallic structures. In case of highly energetic reactions, sputtering of products was also experienced, in some extreme cases with the shattering of the crucibles containing the reactants.
- Pre-processing of the reactants (for example ball milling) proved to have the potential to improve the propagation. However, this aspect was not fully investigated, and it is proposed to test in a later stage of the project, when a full ISRU architecture of ACME could be validated.

- Post-processing of the products was relatively easy in the case of powdery and brittle samples. In particular, the products of thermite from ilmenite produced a highly magnetic powder which indicates high content of iron. This could potentially be used for ISRU additive manufacturing or casting applications.
- The extraction and the quantification of the energy generation and transfer was made inaccurate from the large losses that were experienced by the current design of the breadboard. In order to improve this characterization, a change in the design of the system is deemed.

For the next stage of the ACME project, Maana has identified the following potential tasks:

- Perform characterization of some selected samples. This was not done during the activity given the complexity in finding an external lab willing to accept testing samples with residuals of unreacted thermite. Currently Maana is discussing with a lab that expressed no such concern and samples could be shipped soon for XRD/XRF analysis.
- Modify/develop further the breadboard for more accurate measurements of the energy and validation of the applicability of the ACME concept for Lunar Night Survival.
- Validate the "closed loop" architecture presented in this document to use ISRU for producing energy during lunar night and regenerate the metal reactant during the lunar day from the oxide product of the thermite reaction.